

Surface-soil responses to paraplowing of long-term no-tillage cropland in the Southern Piedmont USA

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Abstract

The type of conservation-tillage management employed could impact surface-soil properties, which could subsequently affect relationships between soil and water quality, as well as with soil C sequestration and greenhouse gas emissions. We determined soil bulk density, organic C and N fractions, plant-available N, and extractable P on Typic Kanhapludults throughout a 7-year period, in which four long-term (>10 years), no-tillage (NT) water catchments (1.3–2.7 ha each) were divided into two treatments: (1) continuation of NT and (2) paraplowing (PP) in autumn (a form of non-inversion deep ripping) with NT planting. Both summer [cotton (*Gossypium hirsutum* L.), maize (*Zea mays* L.), sorghum (*Sorghum bicolor* L. Moench), soybean (*Glycine max* L. Merr.)] and winter [wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), rye (*Secale cereale* L.), crimson clover (*Trifolium incarnatum* L.)] crops were NT planted throughout the study under each management system. Soil bulk density was reduced with PP compared with NT by as much as 0.15 Mg m⁻³, but the extent of reduction was inversely related to the time lag between PP operation and sampling event. Soil organic C became significantly enriched with time during this study under NT (0.49 Mg C ha⁻¹ year⁻¹), but not under PP, in which poultry litter was applied equivalent to 5.7 Mg ha⁻¹ year⁻¹ to all water catchments. Soil maintained a highly stratified depth distribution of organic C and N fractions and extractable P under both NT and PP. Inability to perform the PP operation in the last year of this study resulted in rapid convergence of soil bulk density between tillage systems, suggesting that PP had <1-year effectiveness on soil loosening. The high energy cost of PP (ca. 30 kW shank⁻¹) and the lack of sustained improvement in surface-soil properties put into question the value of PP for improving upon long-term NT management in sandy loam and sandy clay loam Ultisols of the Southern Piedmont USA, unless large effects on crop yield, water quality, or other ecosystem processes warrant its use.

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1. Introduction

Tillage system is an important management variable that influences long-term agricultural sustainability. Inversion tillage systems are effective in loosening soil, but the effect is usually short-lived (Voorhees and

Lindstrom, 1984; Franzluebbers et al., 1995) and causes accelerated decomposition of organic matter (Giddens, 1957) and loss of soil through erosion (Trimble, 1974). Amelioration of eroded cropland in the southeastern USA has been advocated through the use of conservation-tillage systems that limit soil disturbance and allow surface residue accumulation (Langdale et al., 1992). The positive effects of conservation tillage were demonstrated in a water-catchment study in the Piedmont of Georgia, whereby runoff of water and associated soil loss were 180 mm year⁻¹ and

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23 Mg ha⁻¹ year⁻¹, respectively, during the first 2.5 years under conventional inversion tillage and 23 mm year⁻¹ and <1 Mg ha⁻¹ year⁻¹, respectively, during the ensuing 24 years following adoption of no-tillage (NT) management (Endale et al., 2000).

Unfortunately, adoption of NT management can initially increase soil bulk density (Voorhees and Lindstrom, 1984), which could negatively affect (i) crop production and subsequent return of crop biomass to the soil, (ii) soil water-nutrient dynamics, and (iii) water runoff relationships. Crop producers often express their concern that compaction under continuous NT cropping could limit water and nutrient distribution in soil, thereby limiting crop rooting depth, overall productivity, and profitability. Deep ripping [i.e., paraplowing (PP)] might be a viable conservation strategy to loosen surface and subsoil without excessive incorporation of surface crop residues (Wesley et al., 2001). The PP tool has a bent-leg shank that can shatter compacted subsoil to a depth of ~40 cm while generally leaving crop residue and surface-soil intact. Ideally, compacted fields would receive PP in the autumn in the southeastern USA, when soil is dry enough to shatter (Wesley et al., 2001). This loosening of subsoil is thought to enhance water and nutrient storage. However, the energy and monetary costs of performing a PP operation are not trivial. Paraplowing requires a tractor with a capacity of ca. 30 kW shank⁻¹, which could cost \$30 ha⁻¹ to operate (Mississippi State University Department of Agricultural Economics, 2006).

Currently, there is a great need for long-term, water-catchment studies to provide information on how changes in soil quality (e.g., surface-soil compaction and organic C, N, and P distribution in soil) induced by tillage management might affect water quality. This information is especially needed under conservation-tillage management systems, in which the accumulation of organic matter and nutrients (especially N and P) at the soil surface can be viewed as a threat to water quality (Sharpley, 2003). Alternatively, the accumulation of surface-soil organic matter could also mitigate water runoff quantity and quality by enhancing water infiltration and reducing the load of nutrients from water runoff (Sharpley et al., 1992). Linkages between soil and water quality are key issues facing producers and agricultural specialists in regions where soil nutrients have become elevated, oftentimes due to frequent animal manure application.

Poultry production in the southeastern USA is extensive (USDA-National Agricultural Statistics Service, 2007), and land application of poultry manure

provides essential nutrients to crops and helps alleviate waste disposal. Poultry manure is often mixed with bedding material at the end of the production cycle, cleared from confinement housing, and applied as litter (manure plus bedding) to nearby land as a source of nutrients. Depending upon management, however, repeated application of poultry litter could become a source of excessive nutrients (Vervoot et al., 1999). Surface application of poultry litter without soil incorporation may potentially cause unwanted nutrient enrichment in surface water runoff, which is of significance in the high-rainfall region of the southeastern USA. Of increasing concern is the unbalanced load of P in poultry litter compared with N. However, since crop production on Ultisols in the southeastern USA benefits greatly from P application as a result of the large capacity for P sorption to soil that limits plant availability, relatively high poultry litter application rates may be possible without causing undesirable water quality effects.

The impact of soil disturbance on soil organic matter and its relationship to greenhouse gas emission has received a great deal of attention recently (Follett, 2001; Franzluebbers and Follett, 2005). Soil organic matter plays a key role in many important agroecosystem processes, including nutrient cycling, water infiltration, prevention of sediment and nutrient loss, and avoiding compaction (Weil and Magdoff, 2004). Active and passive fractions of soil organic matter, including soil microbial biomass, potential N mineralization, and particulate organic matter, have been widely used to identify shifts in soil organic matter due to subtle management differences (Wander, 2004).

We conducted a paired, replicated water-catchment study to quantify relationships between soil and water quality. Our working hypothesis was that PP could be an effective tillage tool to increase water infiltration and movement of nutrients to deeper soil layers, but that would not excessively disturb the vitally important surface-soil condition (i.e., enriched in soil organic matter) necessary for sequestration of soil organic C, mitigation of traffic-induced compaction, maintenance of well-aggregated soil, and prevention of nutrient loss from water runoff. Our objective was to evaluate the multiple-year effects of NT compared with PP on surface-soil distribution of bulk density, organic C and N fractions, plant-available N, and extractable P. Preliminary surface water runoff volume and nutrient concentration were reported (Endale et al., 2002), but a more complete analysis is pending to help us link issues of soil and water quality. Our focus in this report is on the soil quality portion of this study.

2. Materials and methods

2.1. Experimental setup

The experiment consisted of a set of four (P1–4) small water catchments (1.3–2.7 ha each) located near Watkinsville, GA (33°52'N, 83°25'W). Soils were mapped primarily as Cecil sandy loam and Cecil sandy clay loam (fine, kaolinitic, thermic Typic Kanhapludults; Orthic Acrisol, FAO) with Pacolet sandy loam (fine, kaolinitic, thermic Typic Kanhapludults) on a shoulder slope near the edge of one landscape and Starr sandy loam (fine-loamy, mixed, semiactive, thermic Fluventic Dystrudepts) in the waterway position of one landscape (R.R. Bruce, unpublished data). These soils were classified as well drained with moderate permeability (Robertson, 1968). Long-term mean annual precipitation is 1250 mm and mean annual temperature is 16.5 °C (Georgia Automated Environmental Monitoring Network, 2007). P1 and P2 catchments were separated by ca. 0.8 km. P3 and P4 catchments were immediately adjacent to each other and separated from P1 by 3.8 km and from P2 by 3 km. Slope ranged from 2 to 7% on P1 and P2 catchments. Slope ranged from 1.5 to 3% on P3 and P4, both of which also contained old terraces.

The four water catchments were developed with earthen borders and runoff instrumentation in 1972–1973 and managed together until 1975 to study pesticide runoff (Leonard et al., 1979). Thereafter, different crop and tillage management systems were employed for different purposes. From 1976 to 1982, the P2 catchment was managed with common bermudagrass (*Cynodon dactylon* L.), while other catchments were cropped annually. Prior to 1998, when this study began, all water catchments were managed for at least 10 years with NT planting of various crops, including barley (*H. vulgare* L.), cotton (*G. hirsutum* L.), forage sorghum (*Sorghum vulgare* Pers.), grain sorghum (*S. bicolor* (L.) Moench), maize (*Z. mays* L.), soybean (*G. max* (L.) Merr.), and wheat (*T. aestivum* L.). Typical cover crops included crimson clover (*T. incarnatum* L.) and rye (*S. cereale* L.).

In the autumn of 1998, the four water catchments were managed together for the purposes of this study. Since the autumn of 1998, P1 and P3 catchments were allowed to continue under continuous NT and P2 and P4 were converted to NT planting of all crops with autumn PP following harvest of the summer crop. Paraplowing depth was 30–40 cm and usually occurred in October/November, except during the final 2 years of the study when excessively dry

Table 1
Cropping, fertilization, tillage, and sampling events in the water-catchment study near Watkinsville GA

Year	Summer crop ^a	Winter crop ^a	Fertilization	Paraplowing	Sampling
1997		P1 + P2 ^b : barley; P3: volunteer crimson clover; P4: rye			
1998	P3 + P4: cotton; P1 + P2: soybean	P1 + P4: rye; P2 + P3: crimson clover	NH ₄ NO ₃ : 45 kg N ha ⁻¹ (P1 + P2 + P3), 90 kg N ha ⁻¹ (P4)	P2 + P4: 10–13 November	
1999	Maize	P1 + P4: rye; P2 + P3: rye/crimson clover	NH ₄ NO ₃ : 134 kg N ha ⁻¹	P2 + P4: 27–28 October	20–21 January
2000	Pearl millet	Rye	Broiler litter: 3.0 Mg ha ⁻¹ (5–6 July)	P2 + P4: 30 October	10–17 February
2001	Grain sorghum	Wheat	Broiler litter: 2.9 Mg ha ⁻¹ (2 July), 4.6 Mg ha ⁻¹ (21 December)	P2 + P4: 26 November	
2002	Grain sorghum	Wheat	Broiler litter: 6.9 Mg ha ⁻¹ (25 June), 4.0 Mg ha ⁻¹ (25 November)		20–22 March
2003	Grain sorghum	Rye	Broiler litter: 6.3 Mg ha ⁻¹ (24 June), 3.1 Mg ha ⁻¹ (17 November)	P2 + P4: 17 November	
2004	Grain sorghum	Volunteer rye/ryegrass	Broiler litter: 5.9 Mg ha ⁻¹ (20 July)		12–14 July
2005	Maize	Rye/crimson clover	Broiler litter: 3.5 Mg ha ⁻¹ (18 April), NH ₄ NO ₃ : 112 kg N ha ⁻¹		20–21 January

^a Barley (*Hordeum vulgare* L.), cotton (*Gossypium hirsutum* L.), crimson clover (*Trifolium incarnatum* L.), maize (*Zea mays* L.), pearl millet (*Pennisetum glaucum* L. R. Br.), rye (*Secale cereale* L.), ryegrass (*Lolium multiflorum* Lam.), sorghum (*Sorghum bicolor* L. Moench), soybean (*Glycine max* L. Merr.), and wheat (*Triticum aestivum* L.).

^b P1, P2, P3, and P4 are 1.3–2.7 ha water catchments managed as individual experimental units since 1972.

conditions prevented its use (Table 1). The PP contained six bent-leg shanks (tip located 0.3 m offset from toolbar shank) spaced 0.6 m apart, except for the two middle shanks, which were spaced 0.3 m apart at the working tips and 0.9 m apart on the toolbar. Inorganic fertilizer was used during the first 2 years and broiler litter fertilizer was used from 2000 onwards (Table 1). Composition of broiler litter varied, but contained significant concentration of C, N, P, K, and Ca (Fig. 1).

2.2. Soil collection and analyses

Soil samples were collected from each water catchment in five zones, which served as pseudoreplicates for analyses. The five zones represented a central waterway and the four corner sections of each catchment. The waterway received runoff from surrounding areas within the catchment and conveyed excess water to a water flume at the lowest portion of the catchment. Within each zone, eight sites separated by ca. 15 m were sampled and composited. Obvious recent PP furrows were avoided, but sampling position was randomly distributed otherwise to adequately represent each field. At each site, any plant material above a 4 cm height (sampling often occurred in the presence of a cover crop) was cut and removed from a 0.04 m² area and then all surface residues were collected to ground level after cutting with a batter-powered hand shears. Samples were collected in years 1, 2, 4, 6, and 7, usually in winter to ensure adequate moisture and to avoid excessive plant biomass accumulation (Table 1). Surface residue was dried (55 °C, ≥3 days), ground to <1 mm, and a subsample was analyzed for total C and N with dry combustion. Following surface residue removal, a soil core (4 cm diameter) was sectioned into depths of 0–3, 3–6, 6–12, and 12–20 cm. Although deeper soil sampling may have detected further changes in soil properties, we were most interested in the impact on organic matter nearest the soil surface and whether any movement of N and P would occur below the surface 6 cm. Soil was dried at 55 °C for ≥3 days and bulk density was calculated from the total dry weight of soil and volume of coring device (Franzluebbers et al., 1999b; Franzluebbers and Brock, 2007). For all subsequent laboratory analyses, soil was passed through a sieve with openings of 4.75 mm to remove stones. A subsample was ground in a ball mill for 5 min and analyzed for total C and N with dry combustion. Soil pH was 6.3 ± 0.1 for samples collected prior to the study in 1998, and therefore,

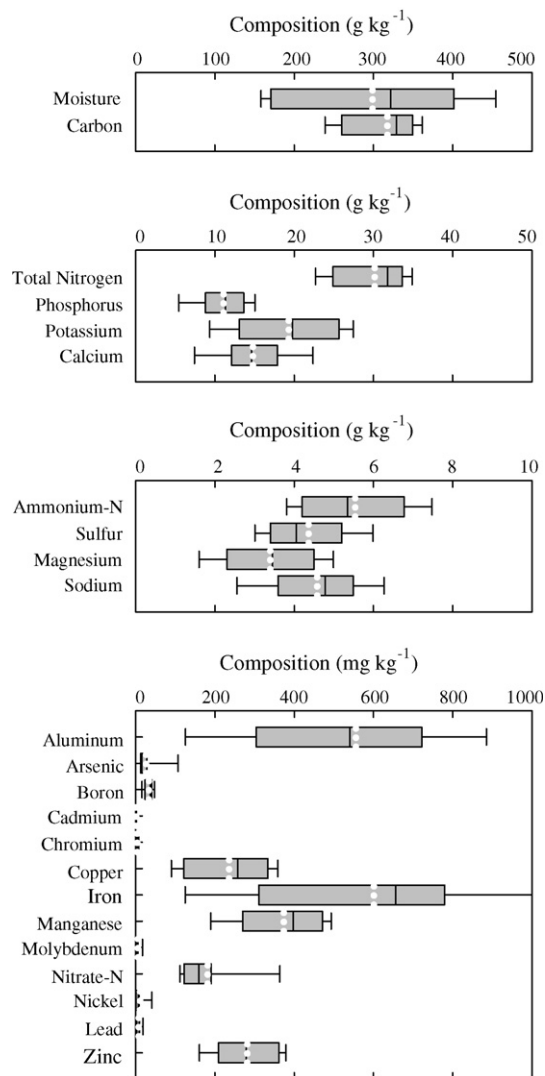


Fig. 1. Analytical composition of poultry litter applied to soil. Values are from 30 samples submitted to the University of Georgia Soil and Plant Testing Laboratory. Boxes represent 25–75th percentiles, error bars represent 10–90th percentiles, solid vertical line represents median, and dotted vertical line represents mean.

total C and N were considered equivalent to organic C and N.

Particulate organic matter was isolated from soil by shaking 20–65 g subsamples of soil (inversely related to soil organic C concentration) in 100 mL of 0.01 M Na₄P₂O₇ for 16 h, passing the mixture over a sieve with 0.053 mm openings, and collecting the contents remaining on the top of the sieve (Cambardella and Elliott, 1992; Franzluebbers et al., 1999b). Samples were dried at 55 °C for 72 h, weighed, ground to a fine powder in a ball mill, and analyzed for C and N concentration with dry combustion (Leco CNS-2000

and Tru-Spec).¹ Clay concentration from soil collected in January 1999 was determined prior to particulate organic matter determination in a 1 L cylinder with a hydrometer at the end of a 5 h settling period (Gee and Bauder, 1986).

Potential C mineralization was determined by placing two 20–65 g subsamples of soil in 60 mL glass jars, wetting to 50% water-filled pore space, and placing them in a 1 L canning jar along with 10 mL of 1 M NaOH to trap CO₂ and a vial of water to maintain humidity (Franzluebbers et al., 1999b). Samples were incubated at 25 ± 1 °C for 24 days. Alkali traps were replaced at 3 and 10 days of incubation and CO₂-C determined by titration with 1 M HCl in the presence of excess BaCl₂ to a phenolphthalein endpoint. At 10 d, one of the subsamples was removed from the incubation jar, fumigated with CHCl₃ under vacuum, vapors removed at 24 h, placed into a separate canning jar along with vials of alkali and water, and incubated at 25 °C for 10 days. Soil microbial biomass C was calculated as the quantity of CO₂-C evolved following fumigation divided by an efficiency factor of 0.41 (Voroney and Paul, 1984; Franzluebbers et al., 1999a). Potential C mineralization was the CO₂-C respired during 24 days, while the flush of CO₂-C following rewetting was considered from the first 3 days only. Potential N mineralization was determined from the difference in inorganic N concentration between 0 and 24 days of incubation. Inorganic N (NH₄-N + NO₂-N + NO₃-N) was determined from the filtered extract of a 10 g subsample of dried (55 °C for 48 h) and sieved (<2 mm) soil that was shaken with 20 mL of 2 M KCl for 30 min using salicylate-nitroprusside and Cd-reduction autoanalyzer techniques (Bundy and Meisinger, 1994). Mehlich-I extractable soil P was determined from the filtered extract of a 10 g subsample of dried (55 °C for 48 h) soil that was shaken with 40 mL of 0.05 M HCl + 0.0125 M H₂SO₄ for 15 min using a molybdate autoanalyzer technique (Olsen and Sommers, 1982).

2.3. Weather conditions

Precipitation was recorded at a nearby weather station (0.1–3 km distance from each watershed) (Georgia Automated Environmental Monitoring Network, 2007). During the 7 years of this study, 1999–

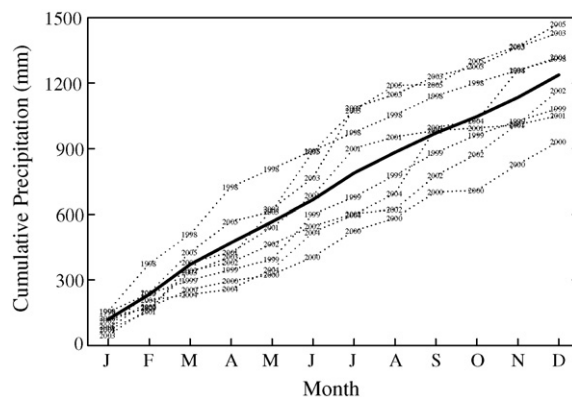


Fig. 2. Cumulative yearly precipitation during 1998–2005 and long-term mean annual precipitation (solid line; 30-year mean) at Watkinsville, Georgia.

2001 had below long-term mean precipitation throughout the year and 2003–2005 had greater than long-term mean precipitation (Fig. 2). By characterizing significant droughts as ≥3 consecutive months with <75% of long-term mean precipitation, droughty periods occurred in all years, except 2005. Droughts occurred from October to November 1998 (64% of long-term mean), February–May 1999 (54% of long-term mean), February–May 2000 (45% of long-term mean), August–December 2001 (34% of long-term mean), April–August 2002 (55% of long-term mean), August–October 2003 (73% of long-term mean), and March–May 2004 (42% of long-term mean). These data are evidence of frequent drought periods common in the region, despite abundant yearly precipitation. Frequent droughts have driven the need for conservation-tillage systems to conserve soil moisture in this region.

2.4. Statistical analyses

Differences in soil properties within a depth increment as affected by tillage management were analyzed for variance using SAS with 10 replicates (i.e., two replicate water catchments × 5 within-catchment positions). The effect of position within the water catchment was analyzed separately with two replications and two tillage treatments as blocking criteria. This separation of analyses allowed no estimation of tillage × position interaction, which was not expected to be significant. The waterway position was expected to have different soil properties than other positions due to accumulation of sediments during historical cropping. Temporal change in soil properties was evaluated with linear regression to provide a single estimate of change with time. Stratification ratio of soil properties

¹ Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the USDA.

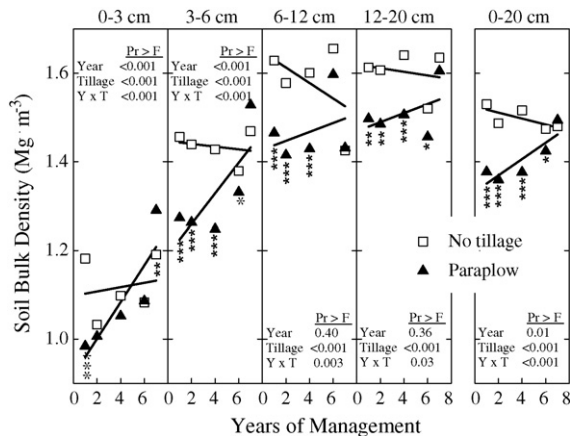


Fig. 3. Soil bulk density as affected by soil depth (0–3, 3–6, 6–12, 12–20, and 0–20 cm), tillage system (no-tillage and paraplow), and sampling event (1, 2, 4, 6, and 7 years of management) when averaged across sampling positions (waterway and four corner sections of each water-catchment). *, **, and *** underneath pairs of tillage means within a sampling year and soil depth indicate significance at $p \leq 0.05$, $p \leq 0.01$, and $p \leq 0.001$, respectively. Solid lines are regression with significance ($Pr > F$) of year (Y), tillage (T), and their interaction noted in each panel.

was calculated from the weighted concentration at a depth of 0–6 cm divided by the concentration at a depth of 12–20 cm (Franzluebbers, 2002). Differences among tillage treatments, sampling positions, and their interactions with time were considered significant at $p \leq 0.05$, but significance of difference was also noted at levels of $p \leq 0.01$ and $p \leq 0.001$ in text, tables, and figures.

3. Results and discussion

3.1. Bulk density

In general, soil bulk density was lowest nearest the soil surface and increased with increasing soil depth (Fig. 3 and Table 2). Paraplowing (PP) resulted in a significant reduction in bulk density at all depth increments, but particularly from 3 to 20 cm (Fig. 3). Bulk density response to tillage system changed with time, in which a large reduction in bulk density (up to 0.2 Mg m^{-3}) occurred with PP compared with NT early in the study, whereas a reversal of tillage effect (at 0–3 cm) or no difference occurred later in the study. Averaged across years, bulk density under NT was greater than under PP at all soil depths, except at 0–3 cm (Table 2).

A leading cause for the temporal change in bulk density due to tillage system was the time lag between sampling events and PP events. Early soil sampling

events occurred closer to PP events than later sampling events. In fact, there was no PP event between the fourth and fifth sampling event. The difference in bulk density between PP and NT was greatest immediately following a PP event (Fig. 4). With increasing time from a PP event, the difference in bulk density between PP and NT diminished. This result was consistent with observations at 3 months and 1 year from PP in a New Zealand cropping system (Hamilton-Manns et al., 2002). Further, the relationship in Fig. 4 suggests that reconsolidation of soil following PP and subsequent tractor traffic would be equivalent at 1 year from a PP event to that with continuous NT. The hypothetical increase in bulk density if soil previously managed with PP were reverted to continuous NT would be a difference of 0.12 Mg m^{-3} , a difference greater than the LSD of 0.07 Mg m^{-3} . On a nearby site with the same soil type, bulk density change in response to PP was slower, in which soil reconsolidation still occurred between 1 and 2 years from a PP event (Franzluebbers et al., 1999b).

3.2. Organic C and N

Soil organic C concentration was greatest nearest the soil surface and declined with depth (Fig. 5; Table 2). This highly stratified distribution of organic C was a consequence of the long-term history of NT preceding this study that allowed crop residues to decompose at the soil surface and enrich the surface with organic matter (Dick, 1983; Franzluebbers, 2002). Paraplowing caused a reduction in soil organic C only at a depth of 0–3 cm during the last two sampling events (Fig. 5). At lower depths (i.e., 3–20 cm), PP often resulted in

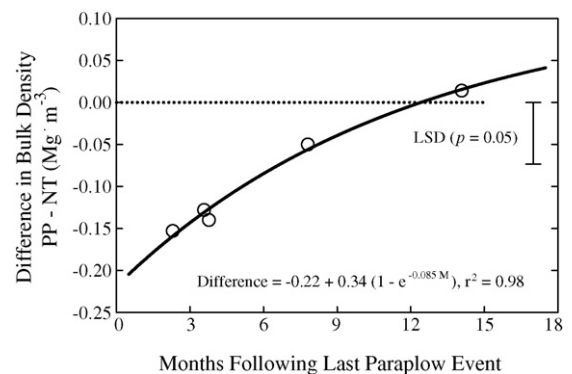


Fig. 4. Difference in soil bulk density between paraplowing (PP) and no-tillage (NT) at a depth of 0–20 cm as affected by sampling event sorted as a function of months elapsed since previous paraplow event when averaged across sampling position (waterway and four corner sections of each water-catchment). Solid curve is non-linear regression with parameters noted in equation.

Table 2

Mean soil responses to tillage (NT, no-tillage; PP, paraplow) and depth when averaged across sampling events (1, 2, 4, 6, and 7 years of management) and sampling position (waterway and four corner sections of each water-catchment)

Tillage	Soil depth (cm)					Stratification ratio (0–6/12–20 cm) (g g ^{−1})
	0–3	3–6	6–12	12–20	0–20	
Soil bulk density (Mg m ^{−3})						
NT	1.12	1.43**	1.58***	1.60***	1.50 Mg ha ^{−1} ***	0.80
PP	1.08	1.33	1.47	1.51	1.41 Mg ha ^{−1}	0.80
Soil organic carbon (g kg ^{−1})						
NT	24.1	12.9	7.5	5.1	26.5 Mg ha ^{−1}	3.5
PP	22.7	15.2*	9.5**	6.1	28.4 Mg ha ^{−1}	3.1
Total soil nitrogen (g kg ^{−1})						
NT	2.25	1.19	0.64	0.41	2.30 Mg ha ^{−1}	5.1
PP	2.04	1.37	0.80*	0.45	2.38 Mg ha ^{−1}	4.9
Particulate organic carbon (g kg ^{−1})						
NT	9.3	3.6	1.7	1.0	7.3 Mg ha ^{−1}	9.0
PP	7.8	4.8*	2.7**	1.1	7.9 Mg ha ^{−1}	7.1
Particulate organic nitrogen (g kg ^{−1})						
NT	0.56	0.28	0.15	0.10	0.55 Mg ha ^{−1}	15.2
PP	0.45	0.32	0.19*	0.10	0.54 Mg ha ^{−1}	10.5
Soil microbial biomass carbon (g kg ^{−1})						
NT	1.13	0.65	0.34	0.23	1.24 Mg ha ^{−1}	4.4
PP	1.11	0.70	0.39	0.24	1.24 Mg ha ^{−1}	4.6
Flush of CO ₂ -C following rewetting of dried soil (mg kg ^{−1} 3 days ^{−1})						
NT	439	217	116	69	427 kg ha ^{−1} 3 days ^{−1}	4.7
PP	442	260**	144***	76	452 kg ha ^{−1} 3 days ^{−1} *	4.8
Potential carbon mineralization (mg kg ^{−1} 24 days ^{−1})						
NT	1249	581	290	162	1119 kg ha ^{−1} 24 days ^{−1}	5.5
PP	1258	682*	364**	188**	1190 kg ha ^{−1} 24 days ^{−1} *	5.2
Potential nitrogen mineralization (mg kg ^{−1} 24 days ^{−1})						
NT	88.3*	38.8	16.6	7.9	66.4 kg ha ^{−1} 24 days ^{−1}	27*
PP	73.6	48.6	23.6*	10.8**	72.0 kg ha ^{−1} 24 days ^{−1}	20
Residual inorganic nitrogen (mg kg ^{−1})						
NT	24	18	18	18	55 kg ha ^{−1}	1.7
PP	23	20	19	18	52 kg ha ^{−1}	1.6
Mehlich-I extractable phosphorus (mg kg ^{−1})						
NT	74	49	33	18	98 kg ha ^{−1}	3.7
PP	70	49	32	12	84 kg ha ^{−1}	6.0**

*, **, and *** indicate means within a soil property and sampling depth are different at $p \leq 0.05$, $p \leq 0.01$, and $p \leq 0.001$, respectively.

significantly greater soil organic C concentration than under NT, which may have been a result of some immediate physical incorporation with the implement, but also subsequent water movement of organic matter into loosened fissures, as well as from potentially greater root activity in this loosened zone. Alternatively, soil properties in these four water catchments may not have been equivalent prior to initiation of this study due to long-term land-use effects and/or landscape position.

Changes in soil organic C with time occurred within the surface 12 cm (Fig. 5). Generally, soil organic C concentration either declined or remained stable under

PP, but increased with time under NT. The stock of soil organic C to a depth of 20 cm increased with time ($p < 0.001$) under NT, but did not change significantly with time ($p = 0.22$) under PP:

$$\begin{aligned} &\text{stock of soil organic C (Mg ha}^{-1}\text{)}_{0-20\text{ cm}} \\ &= \left\{ \begin{array}{l} 24.5 + 0.490 (\text{years}), \quad r^2 = 0.82 \quad [\text{NT}] \\ 27.6 + 0.180 (\text{years}), \quad r^2 = 0.86 \quad [\text{PP}] \end{array} \right\} \end{aligned}$$

These estimates of soil organic C sequestration are within the range of typical values for the region. In fact the rate of soil organic C sequestration under NT

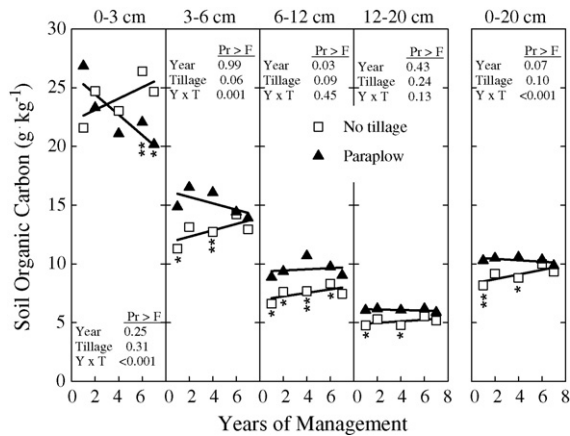


Fig. 5. Soil organic C as affected by soil depth (0–3, 3–6, 6–12, 12–20, and 0–20 cm), tillage system (no-tillage and paraplow), and sampling event (1, 2, 4, 6, and 7 years of management) when averaged across sampling position (waterway and four corner sections of each water-catchment). * and ** underneath pairs of tillage means within a sampling year and soil depth indicate significance at $p \leq 0.05$ and $p \leq 0.01$, respectively. Solid lines are regression with significance ($\text{Pr} > F$) of year (Y), tillage (T), and their interaction noted in each panel.

($0.49 \text{ Mg C ha}^{-1} \text{ year}^{-1}$) is very similar to the mean rate of soil organic C sequestration for NT cropping systems with cover cropping ($0.53 \text{ Mg C ha}^{-1} \text{ year}^{-1}$) in the southeastern USA (Franzluebbers, 2005). The estimate of soil organic C sequestration in the current study was during the 25th–31st year of continuous NT on P1 and mostly NT and intermittent conventional tillage on P3.

Stock estimates of soil organic C were based on equal volume of soil to a depth of 20 cm. However, Ellert and Bettany (1995) raised the awareness that stock estimates of organic C and N based on equal volume could be biased when management causes differences in bulk density. They suggested calculating stock of soil organic C and N based on equal mass. This approach can be valid if sufficiently detailed soil depth increments have been sampled. The highest bulk density at a depth of 0–20 cm was 1.53 Mg m^{-3} in Year 1 under NT (Fig. 3). With this level as a benchmark (i.e., 306 kg m^{-2}), estimates of stock changes in soil organic C were $0.52 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ under NT and $-0.04 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ under PP. Estimates of change in soil organic C stock based on equal mass did not differ appreciably from estimates based on equal volume, at least in terms of significance from zero.

Residue C and N contents increased with time ($p < 0.001$) under both tillage systems. Carbon content of surface residue averaged across sampling periods was unaffected by tillage system (3.8 Mg ha^{-1} versus

3.6 Mg ha^{-1} under NT and PP, respectively, $p = 0.14$), but N content of surface residue was greater ($p = 0.05$) under NT (0.17 Mg ha^{-1}) than under PP (0.14 Mg ha^{-1}). Slightly greater surface residue N content (and tendency for greater surface residue C) with NT may have been due to a small amount of residue incorporated into soil from fissures created by PP. The combined stock of organic C in surface residue and soil increased with time ($p < 0.01$) under both tillage systems:

$$\text{stock of C (residue + soil) (Mg ha}^{-1}\text{)} = \begin{cases} 27.1 + 0.806 (\text{years}), & r^2 = 0.78 \quad [\text{NT}] \\ 29.7 + 0.565 (\text{years}), & r^2 = 0.81 \quad [\text{PP}] \end{cases}$$

One of the reasons for the increase in the stock of organic C with time may have been the frequent addition of broiler litter throughout the course of this study (Table 1). From analyses of broiler litter ($n = 30$), C composition averaged 318 g kg^{-1} (Fig. 1), which combined with the 40.1 Mg ha^{-1} applied during the course of this study supplied $12.8 \text{ Mg C ha}^{-1}$. The increase in stock of organic C, therefore, represented 31–44% of the C applied with broiler litter. Not all of the change in stock of organic C should be solely attributed to the addition of broiler litter, since the cropping systems employed had cover crops and high-biomass-producing summer crops that would have also contributed to the increase in stock of organic C.

Total soil N was also highly stratified with depth (Table 2). Tillage system did not influence total soil N, except at a depth of 6–12 cm, in which: PP > NT. Changes in total soil N with time occurred only at a depth of 0–3 and 3–6 cm. Within the surface 20 cm, total soil N did not change significantly with time under either tillage system. There was an increase in residue N content with time in both tillage systems, but the net change in stock of total N was still not different from zero. The supply of N from the 40.1 Mg ha^{-1} of broiler litter was 1210 kg ha^{-1} (based on 30 g N kg^{-1} broiler litter, Fig. 1). Inorganic N application during the study was 291–336 kg ha^{-1} for a total average supply of 214–221 $\text{kg total N ha}^{-1} \text{ year}^{-1}$. It seems that this amount of N was necessary to maintain total soil N and provide enough available N to crops.

Particulate organic C and N were even more highly stratified with depth than soil organic C and total N (Table 2). Concentration of particulate organic C and N at a depth of 0–20 cm was not affected by tillage system, but differences did occur within a few depth increments, especially at 3–12 cm, in which: PP > NT. These data suggest that the fissures in soil created by PP may have allowed some vertical displacement of organic matter. It

is also possible that the increase in particulate organic C and N could have been due to improved rooting in this zone due to lower bulk density. Our procedure for the isolation of particulate organic matter did not distinguish roots from semi-decomposed crop residues. At a depth of 0–20 cm, particulate organic C was an average of 28% of soil organic C and particulate organic N was an average of 23% of total soil N. Particulate organic C as a fraction of soil organic C was greater near the surface (i.e., 36% at a depth of 0–3 cm) and declined with depth, but the fraction of total N as particulate organic N was relatively uniform with depth. Similar proportions were reported for other shorter-term, conservation-tillage management systems on the same soil type (Franzluebbers et al., 1999b).

3.3. Biologically active C fractions

Potential C mineralization during 24 days of incubation was highly stratified with depth, similar to total and particulate organic C (Fig. 6 and Table 2). Unlike soil organic C, potential C mineralization declined with time during this study at all depths (Fig. 6). The decline was always greater under PP than under NT. Initially, potential C mineralization was greater under PP than under NT, but towards the end of the study, there was no difference between PP and NT. The reason for this decline with time is not clear, since neither tillage system should have stimulated decomposition excessively and

there was continual addition of organic C with broiler litter and crop residues. Averaged across sampling events, potential C mineralization was greater under PP than under NT at all depths, except 0–3 cm (Table 2).

Soil microbial biomass C followed a similar pattern to that of potential C mineralization with respect to depth distribution (Table 2). However, there was no difference in soil microbial biomass C between tillage systems at any depth. Soil microbial biomass C at a depth of 0–20 cm also declined significantly with time under both NT ($-16 \text{ mg kg}^{-1} \text{ year}^{-1}$, $p = 0.002$) and PP ($-31 \text{ mg kg}^{-1} \text{ year}^{-1}$, $p < 0.001$).

The flush of $\text{CO}_2\text{-C}$ following rewetting of dried soil exhibited a similar pattern to that of potential C mineralization with respect to depth distribution and tillage effect (Table 2). The flush of $\text{CO}_2\text{-C}$ at a depth of 0–20 cm was unchanged with time under NT ($-1 \text{ mg kg}^{-1} \text{ year}^{-1}$, $p = 0.47$), but declined with time under PP ($-8 \text{ mg kg}^{-1} \text{ year}^{-1}$, $p < 0.001$). The flush of $\text{CO}_2\text{-C}$ was greater under PP than under NT during the first three sampling events, but not different between tillage systems at the final two sampling events. The flush of $\text{CO}_2\text{-C}$ was highly related to soil microbial biomass C, potential N mineralization, particulate organic C, and soil organic C (Fig. 7). Similarly strong

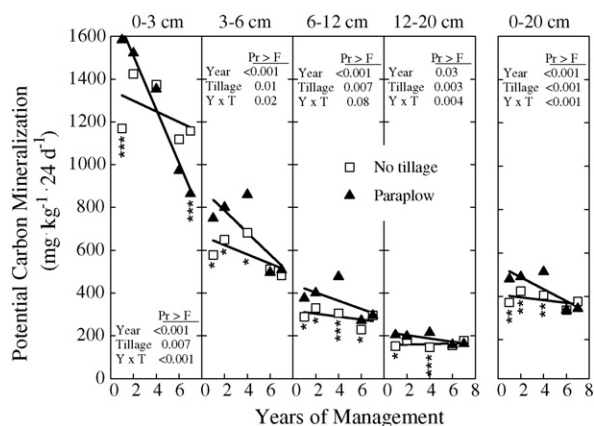


Fig. 6. Potential C mineralization during 24 days of aerobic incubation at 25 °C and 50% water-filled pore space as affected by soil depth (0–3, 3–6, 6–12, 12–20, and 0–20 cm), tillage system (no-tillage and paraplow), and sampling event (1, 2, 4, 6, and 7 years of management) when averaged across sampling position (waterway and four corner sections of each water-catchment). *, **, and *** underneath pairs of tillage means within a sampling year and soil depth indicate significance at $p \leq 0.05$, $p \leq 0.01$, and $p \leq 0.001$, respectively. Solid lines are regression with significance ($\text{Pr} > F$) of year (Y), tillage (T), and their interaction noted in each panel.

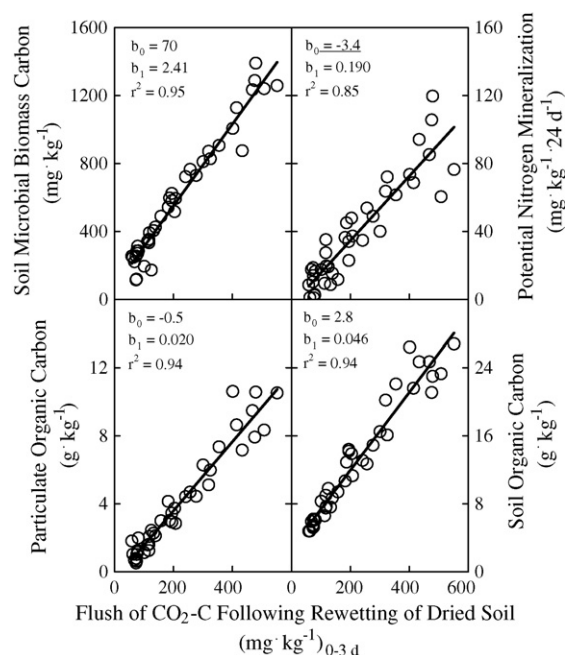


Fig. 7. Relationship of soil microbial biomass C, net N mineralization, particulate organic C, and soil organic C to the flush of $\text{CO}_2\text{-C}$ during 3 days of aerobic incubation at 25 °C following rewetting (50% water-filled pore space) of dried soil. Solid lines are regression with parameters in each panel, where b_0 is the intercept and b_1 is the slope.

relationships between the flush of $\text{CO}_2\text{-C}$ following rewetting of dried soil and various other C and N fractions were reported previously for a diversity of soils in Alberta, British Columbia, Maine, and Texas (Franzluebbers et al., 2000), for native and reclaimed mine soils in Wyoming (Ingram et al., 2005), for Ultisols in North Carolina (Franzluebbers and Brock, 2007), and for Oxisols in Brazil (Green et al., 2006). The flush of $\text{CO}_2\text{-C}$ could be considered a more rapid, yet reliable indicator of potential soil biological activity. Our results indicate that PP did not cause deterioration of surface-soil biological potential, but enhanced soil biological potential at depths of 3–20 cm.

3.4. Available N and extractable P

Residual inorganic N was relatively uniformly distributed in the soil profile, unlike total and particulate organic N fractions (Table 2). Inorganic N was not different between tillage systems at any soil depth. Residual inorganic N at a depth of 0–20 cm declined with time ($p < 0.001$) in both tillage systems at a rate of $10 \text{ kg ha}^{-1} \text{ year}^{-1}$ from an initial value of 94 kg N ha^{-1} . The decline with time in residual inorganic N may have been due to a switch in the predominant source of N supply from inorganic N nearly in the study to broiler litter during most of the study. Although broiler litter contained an average of $5.5 \text{ g NH}_4\text{-N kg}^{-1}$ litter and $181 \text{ mg NO}_3\text{-N kg}^{-1}$ litter (Fig. 1), the quantity of inorganic N supplied with broiler litter averaged only 25 kg N ha^{-1} per application event. The majority of N in broiler litter would, therefore, have required time and a suitable environment for microbial decomposition to transform organically bound N to inorganic N. Volatilization of NH_3 during the first week after three broiler litter application events (July 2000, July 2001, and December 2001) on two of the water catchments was estimated as $107 \pm 96 \text{ g kg}^{-1}$ total N applied (Sharpe et al., 2004).

Potential N mineralization was highly stratified with depth, similar to other organic C and N fractions (Table 2). Averaged across sampling events, potential N mineralization was greater under NT than under PP at a depth of 0–3 cm, but was lower under NT than under PP at depths of 6–12 and 12–20 cm. With time, potential N mineralization increased significantly under both tillage systems at an average rate of $8.0 \text{ kg N ha}^{-1} \text{ year}^{-1}$ ($p < 0.001$) from an initial supply of 37 kg N ha^{-1} . The increase in potential N mineralization with time was likely due to the application of broiler litter, which contained a large supply of organic N.

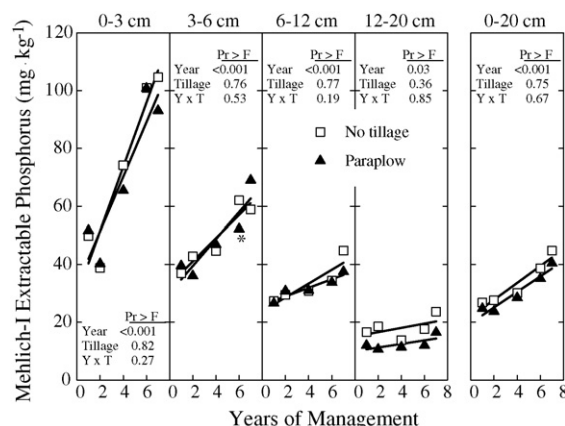


Fig. 8. Mehlich-I extractable soil P as affected by soil depth (0–3, 3–6, 6–12, 12–20, and 0–20 cm), tillage system (no-tillage and paraplow), and sampling event (1, 2, 4, 6, and 7 years of management) when averaged across sampling position (waterway and four corner sections of each water-catchment). * underneath pairs of tillage means within a sampling year and soil depth indicate significance at $p \leq 0.05$. Solid lines are regression with significance ($Pr > F$) of year (Y), tillage (T), and their interaction noted in each panel.

Mehlich-I extractable P was also highly stratified with soil depth, although less so earlier in the study than later (Fig. 8 and Table 2). Tillage system had no impact on extractable P, which was contrary to our expectation. With time in this study, Mehlich-I extractable P increased significantly under both tillage systems at all soil depths (Fig. 8). At a depth of 0–20 cm, Mehlich-I extractable P increased at an average rate of $8.4 \text{ kg PO}_4\text{-P ha}^{-1} \text{ year}^{-1}$ ($p < 0.001$) from an initial supply of $58 \text{ kg PO}_4\text{-P ha}^{-1}$. The doubling of extractable P within 7 years of management was likely due to the application of broiler litter, which contained an average of 11 g P kg^{-1} litter (Fig. 1). Based on the 40.1 Mg ha^{-1} of total broiler litter applied in this study, the increase of $59 \text{ kg PO}_4\text{-P ha}^{-1}$ (i.e., $8.4 \text{ kg ha}^{-1} \times 7$ years) represented only 13% of the total P applied with broiler litter. A large majority of total P applied with litter, therefore, appears to have been either: (i) harvested in grain, (ii) lost in runoff, (iii) leached below the depth of sampling, or (iv) bound in soil as mineral associations. Removal of P in harvested grain (e.g., corn, sorghum, soybean, wheat, barley) could be expected to be $5\text{--}15 \text{ kg ha}^{-1} \text{ year}^{-1}$ depending upon yield and crop (Beaton et al., 1995). During the first 2.5 years of this study (February 1999–July 2001), water runoff averaged 15 mm year^{-1} and P runoff loss averaged $0.5\text{--}2.0 \text{ kg PO}_4\text{-P ha}^{-1} \text{ year}^{-1}$ (Endale et al., 2002). Leaching of P through the soil profile is not considered significant in Ultisols, but $\text{PO}_4\text{-P}$ leaching could have been up to 1 kg ha^{-1} , assuming

$0.2 \pm 0.1 \text{ mg PO}_4\text{-P L}^{-1}$ collected in leachate from a nearby study (Endale et al., 2004) and 500 mm of leachate (40% of mean precipitation). Precipitation as inorganic phosphates or sorption of P to Fe- and Al-oxides and clay minerals are considered primary mechanisms limiting the availability of P in Ultisols characteristic of the southeastern USA (Frossard et al., 1995). Fixation of P in soil was likely the largest component of unaccounted P.

The lack of difference in Mehlich-I extractable P between tillage systems was contrary to our original hypothesis. However, it is still possible that some P may have moved down the soil profile following loosening of the soil with PP. Phosphorus could have undergone significant interaction with subsurface clay minerals, which were in greater concentration than at the soil surface (Table 3), resulting in our inability to detect this change as Mehlich-I extractable P. Further

Table 3

Mean soil properties as affected by sampling position (waterway and four corner sections of each water-catchment) and depth of sampling when averaged across sampling events (1, 2, 4, 6, and 7 years of management) and tillage system (no-tillage and paraplow)

Sampling position	Soil depth (cm)				
	0–3	3–6	6–12	12–20	0–20
Clay fraction (g kg^{-1})					
Waterway	220*	226**	207*	284**	244**
Others	185	167	158	204	182
Soil bulk density (Mg m^{-3})					
Waterway	1.07	1.37	1.49	1.52	1.42
Others	1.11*	1.39	1.53	1.57	1.46
Soil organic carbon (g kg^{-1})					
Waterway	30.8**	18.3*	10.6	7.0	12.4*
Others	21.5	12.9	8.0	5.2	9.0
Total soil nitrogen (g kg^{-1})					
Waterway	3.02**	1.83**	0.93	0.56*	1.12**
Others	1.92	1.14	0.67	0.39	0.75
Particulate organic carbon (g kg^{-1})					
Waterway	10.3*	5.1	2.6	1.2	3.2
Others	8.1	4.0	2.1	1.1	2.6
Particulate organic nitrogen (g kg^{-1})					
Waterway	0.61*	0.34	0.18	0.08	0.21
Others	0.47	0.29	0.17	0.10	0.19
Soil microbial biomass carbon (mg kg^{-1})					
Waterway	1310**	801	420	240	493*
Others	1073	646	352	237	423
Flush of $\text{CO}_2\text{-C}$ following rewetting of dried soil ($\text{mg kg}^{-1} 3 \text{ days}^{-1}$)					
Waterway	529**	315**	163**	91*	194***
Others	418	220	122	68	146
Potential carbon mineralization ($\text{mg kg}^{-1} 24 \text{ days}^{-1}$)					
Waterway	1467**	803**	402**	208*	492***
Others	1200	589	308	166	387
Potential nitrogen mineralization ($\text{mg kg}^{-1} 24 \text{ days}^{-1}$)					
Waterway	109**	69*	27	13	35**
Others	74	37	18	8	22
Residual inorganic nitrogen (mg kg^{-1})					
Waterway	29***	25***	24*	22***	24***
Others	22	18	18	17	18
Mehlich-I extractable phosphorus (mg kg^{-1})					
Waterway	77	50	33	16	33
Others	71	49	33	15	32

*, **, and *** indicate means within a soil property and sampling depth are different at $p \leq 0.05$, $p \leq 0.01$, and $p \leq 0.001$, respectively.

investigation of P transformations in the soil profile is warranted.

3.5. Spatial distribution of soil properties

The proportion of total variation explained by sampling sections within a water-catchment was $2.2 \pm 1.9\%$ among the 11 soil properties listed in Table 2. The extent of variation explained by replicate water catchments was $1.8 \pm 2.2\%$, indicating that pseudoreplicates within the water-catchment captured at least as much variation as true replicates.

Differences in soil properties within a water-catchment were almost always due to the comparison between the waterway and other positions. Compared with the rest of the water-catchment, the waterway contained greater clay fraction, soil organic C, total soil N, soil microbial biomass C, flush of $\text{CO}_2\text{-C}$, potential C and N mineralization, and residual inorganic N (Table 3). At a depth of 0–20 cm, there was no difference in bulk density, particulate organic C and N, and Mehlich-I extractable P between the waterway and other positions. The waterway of these water catchments could be characterized as a zone of accumulation for the nutrient-rich sediments deposited from erosion of the upland positions, which would have occurred throughout the cultivation history of this landscape (Bruce et al., 1985). Adoption of conservation-tillage management practices during recent decades shifted the process of redistribution of soil organic matter and nutrients from one that occurred primarily in the horizontal direction via erosive processes to one that occurred in the vertical direction via surface residue accumulation.

4. Conclusions

Long-term NT management created a highly stratified depth distribution of organic C and N fractions in soil. Loosening of soil with PP was effective, but for <1 year only. Disturbance of surface-soil properties with PP was minor, allowing the positive accumulation of surface organic C and N fractions to be maintained. We observed no evidence of enhanced movement of Mehlich-I extractable P deeper into the soil profile with PP. Therefore, in light of the high energy cost of operating the PP and finding few positive, long-lasting effects on soil properties, PP is not recommended for enhancing long-term NT management of sandy loam to sandy clay loam Ultisols in the Southern Piedmont USA, unless large effects on crop yield, water quality, or other ecosystem processes warrant its use.

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References

- Beaton, J.D., Roberts, T.L., Halstead, E.H., Cowell, L.E., 1995. Global transfers of P in fertilizer materials and agricultural commodities. In: Tiessen, H. (Ed.), *Phosphorus in the Global Environment: Transfers, Cycles and Management*, SCOPE 54. John Wiley & Sons, Chichester, England, pp. 7–26.
- Bruce, R.R., Leonard, R.A., Thomas, A.W., Jackson, W.A., 1985. Redistribution of bromide by rainfall infiltration into a Cecil sandy loam landscape. *J. Environ. Qual.* 14, 439–445.
- Bundy, L.G., Meisinger, J.J., 1994. Nitrogen availability indices. In: Weaver, R.W., Angle, J.S., Bottomley, P.S. (Eds.), *Methods of Soil Analysis. Part 2. Soil Sci. Soc. Am. Book Ser. 5. Soil Sci. Soc. Am.*, Madison, WI, pp. 951–984.
- Camardella, C.A., Elliott, E.T., 1992. Particulate soil organic-matter changes across a grassland cultivation sequence. *Soil Sci. Soc. Am. J.* 56, 777–783.
- Dick, W.A., 1983. Organic carbon, nitrogen and phosphorus concentrations and pH profiles as affected by tillage intensity. *Soil Sci. Soc. Am. J.* 47, 102–107.
- Ellert, B.H., Bettany, J.R., 1995. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. *Can. J. Soil Sci.* 75, 529–538.
- Endale, D.M., Schomberg, H.H., Steiner, J.L., 2000. Long-term sediment yield and mitigation in a small Southern Piedmont watershed. *Int. J. Sediment. Res.* 14, 60–68.
- Endale, D.M., Schomberg, H.H., Franzluebbers, A.J., Sharpe, R.R., Jenkins, M.B., 2002. Impact of deep ripping of previous no-tillage cropland on runoff and water quality. In: *Proceedings of the 25th Southern Conserv. Tillage Conf. for Sustainable Agric.*, Auburn, AL, June 24–26, pp. 256–260.
- Endale, D.M., Schomberg, H.H., Jenkins, M.B., Cabrera, M.L., Radcliffe, D.R., Hartel, P.G., Shappell, N.W., 2004. Tillage and N-fertilizer source effects on yield and water quality in a corn-rye cropping system. In: *Proceedings of the 26th Southern Conserv. Tillage Conf. for Sustainable Agric.* Raleigh, NC, June 8–9, CD-ROM, pp. 37–48.
- Follett, R.F., 2001. Soil management concepts and carbon sequestration in cropland soils. *Soil Till. Res.* 61, 77–92.
- Franzluebbers, A.J., 2002. Soil organic matter stratification ratio as an indicator of soil quality. *Soil Till. Res.* 66, 95–106.
- Franzluebbers, A.J., 2005. Soil organic carbon sequestration and agricultural greenhouse gas emissions in the southeastern USA. *Soil Till. Res.* 83, 120–147.
- Franzluebbers, A.J., Brock, B.G., 2007. Surface-soil responses to silage cropping intensity on a Typic Kanhapludult in the piedmont of North Carolina. *Soil Till. Res.* 93, 126–137.

- Franzluebbers, A.J., Follett, R.F., 2005. Greenhouse gas contributions and mitigation potential in agricultural regions of North America: introduction. *Soil Till. Res.* 83, 1–8.
- Franzluebbers, A.J., Hons, F.M., Zuberer, D.A., 1995. Tillage and crop effects on seasonal dynamics of soil CO₂ evolution, water content, temperature, and bulk density. *Appl. Soil Ecol.* 2, 95–109.
- Franzluebbers, A.J., Haney, R.L., Hons, F.M., 1999a. Relationships of chloroform fumigation–incubation to soil organic matter pools. *Soil Biol. Biochem.* 31, 395–405.
- Franzluebbers, A.J., Langdale, G.W., Schomberg, H.H., 1999b. Soil carbon, nitrogen, and aggregation in response to type and frequency of tillage. *Soil Sci. Soc. Am. J.* 63, 349–355.
- Franzluebbers, A.J., Haney, R.L., Honeycutt, C.W., Schomberg, H.H., Hons, F.M., 2000. Flush of carbon dioxide following rewetting of dried soil relates to active organic pools. *Soil Sci. Soc. Am. J.* 64, 613–623.
- Frossard, E., Brossard, M., Hedley, M.J., Metherell, A., 1995. Reactions controlling the cycling of P in soils. In: Tiessen, H. (Ed.), *Phosphorus in the Global Environment: Transfers, Cycles and Management*, SCOPE 54. John Wiley & Sons, Chichester, England, pp. 107–137.
- Gee, G.W., Bauder, J.W., 1986. Particle-size analysis. In: Klute, A. (Ed.), *Methods of Soils Analysis*. Part 2. 2nd ed. Agron. Monogr. 9. Am. Soc. Agron., Soil Sci. Soc. Am., Madison, WI, pp. 383–411.
- Georgia Automated Environmental Monitoring Network, 2007. Online at www.griffin.uga.edu/aemn/cgi-bin/AEMN.pl?site=GAWU, verified 11 June 2007.
- Giddens, J., 1957. Rate of loss of carbon from Georgia soils. *Soil Sci. Soc. Am. Proc.* 21, 513–515.
- Green, V.S., Stott, D.E., Cruz, J.C., Curl, N., 2006. Tillage impacts on soil biological activity and aggregation in a Brazilian Cerrado Oxisol. *Soil Till. Res.* 92, 114–121.
- Hamilton-Manns, M., Ross, C.W., Horne, D.J., Baker, C.J., 2002. Subsoil loosening does little to enhance the transition to no-tillage on a structurally degraded soil. *Soil Till. Res.* 68, 109–119.
- Ingram, L.J., Schuman, G.E., Stahl, P.D., Spackman, L.K., 2005. Microbial respiration and organic carbon indicate nutrient cycling recovery in reclaimed soils. *Soil Sci. Soc. Am. J.* 69, 1737–1745.
- Langdale, G.W., West, L.T., Bruce, R.R., Miller, W.P., Thomas, A.W., 1992. Restoration of eroded soil with conservation-tillage. *Soil Technol.* 5, 81–90.
- Leonard, R.A., Langdale, G.W., Fleming, W.G., 1979. Herbicide runoff from upland piedmont watersheds—data and implications for modeling pesticide transport. *J. Environ. Qual.* 8, 223–229.
- Mississippi State University Department of Agricultural Economics, 2006. Cotton 2006 planning budgets. 2005–01. Mississippi State University, MS.
- Olsen, S.R., Sommers, L.E., 1982. Phosphorus. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), *Methods of Soil Analysis*. Part 2. Chemical and Microbiological Properties, 2nd ed. Agron. Monogr. 9. Am. Soc. Agron., Soil Sci. Soc. Am., Madison, WI, pp. 403–430.
- Robertson, S.M., 1968. Soil Survey of Clarke and Oconee Counties, Georgia. USDA Soil Conservation Service in Cooperation with Univ. Georgia, Coll. Agric., Agric. Expt. Stations. U.S. Govt. Printing Off., Washington, DC.
- Sharpe, R.R., Schomberg, H.H., Harper, L.A., Endale, D.M., Jenkins, M.B., Franzluebbers, A.J., 2004. Ammonia volatilization from surface-applied poultry litter under conservation-tillage management practices. *J. Environ. Qual.* 33, 1183–1188.
- Sharpley, A.N., 2003. Soil mixing to decrease surface stratification of phosphorus in manured soils. *J. Environ. Qual.* 32, 1375–1384.
- Sharpley, A.N., Smith, S.J., Jones, O.R., Berg, W.A., Coleman, G.A., 1992. The transport of bioavailable P in agricultural runoff. *J. Environ. Qual.* 21, 30–35.
- Trimble, S.W., 1974. Man-induced Soil Erosion on the Southern Piedmont, 1700–1970. *Soil Conserv. Soc. Am.*, Ankeny, IA, p. 180.
- USDA-National Agricultural Statistics Service, 2007. 2002 Census of agriculture, United States Department of Agriculture. Accessed at www.nass.usda.gov/census_of_agriculture/index.asp, verified 11 June 2007.
- Vervoot, R.W., Radcliffe, D.E., Cabrera, M.L., Latimore Jr., M., 1999. Field scale nitrogen and phosphorus losses from hay fields receiving fresh and composted broiler litter. *J. Environ. Qual.* 27, 1246–1254.
- Voorhees, W.B., Lindstrom, M.J., 1984. Long-term effects of tillage method on soil tilth independent of wheel traffic compaction. *Soil Sci. Soc. Am. J.* 48, 152–156.
- Voroney, R.P., Paul, E.A., 1984. Determination of k_C and k_N in situ for calibration of the chloroform fumigation–incubation method. *Soil Biol. Biochem.* 16, 9–14.
- Wander, M., 2004. Soil organic matter fractions and their relevance to soil function. In: Magdoff, F., Weil, R.R. (Eds.), *Soil Organic Matter in Sustainable Agriculture*. CRC Press, Boca Raton, FL, pp. 67–102.
- Weil, R.R., Magdoff, F., 2004. Significance of soil organic matter to soil quality and health. In: Magdoff, F., Weil, R.R. (Eds.), *Soil Organic Matter in Sustainable Agriculture*. CRC Press, Boca Raton, FL, pp. 1–43.
- Wesley, R.A., Elmore, C.D., Spurlock, S.R., 2001. Deep tillage and crop rotation effects on cotton, soybean, and grain sorghum on clayey soils. *Agron. J.* 93, 170–178.